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Long-Term Effects of Earthquake-Induced Slope Failures

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ABSTRACT

The earthquake-induced slope failures are now attracting significant concerns among experts of landslides. The reason for this is the complicated causative mechanisms as well as its impact on communities. The present paper states moreover that the onset of seismic slope failure is not only the consequence of a natural disaster but also the beginning of a long-term disaster in which the compound effects of the preceding earthquakes and the following heavy rain falls play significant roles. After addressing cases of this kind of natural disaster together with their classifications, study is made of the material properties of rocks subjected to this long-term procedure. Then, because it is difficult to mechanically stabilize the long-term unstable slopes, an early-warning technology as a practical mitigation measure is introduced.

INTRODUCTION

Slope failure caused by strong earthquake shaking has been one of the typical and important kinds of seismic threats. Because their causative mechanisms consist not only of material properties and gravity forces but also of a complicated seismic loads, their study has many new issues and is interesting. While such slope failures with a huge scale as those of Mt. Huascaran in 1970 (Plafker et al., 1971) and Danguangbao in 2008 with the failure volume of 780 million m^3 (Huang et al., 2008) are very attractive to academic disciplines, it should be stressed that small slope failures are equally important because they affect emergency traffics and make rescue difficult in mountainous regions.

Recently, disaster mitigation engineering is paying increasing attention to extreme events or compound effects. The latter means that two or more causative mechanisms of natural disaster occur simultaneously or sequentially and aggravate the consequent damage. The probability of simultaneous occurrence two mechanisms may sound low but the recent people's demand require such an extreme situation to be taken into some consideration.

The present paper first addresses some examples of compound effects for illustration purposes, and, second, presents more detailed knowledge of compound effects by showing cases of slope failures after earthquakes. Finally, practical solution to this problem is discussed.

EXAMPLES OF COMPOUND DISASTER MECHANISMS

The first example is taken from a river levee. Traditionally, seismic resistant design was not compulsory in river levees because the probability of simultaneous occurrence of strong earthquake and flooding was considered to be low enough. Hence, in case of any seismic damage, quick restoration before the occurrence of flooding has been the engineering objective. This principle failed during the 1995 Kobe earthquake when Yodo-River levee was destroyed by liquefaction (Fig. 1).

Fig. 1. Liquefaction-induced distortion of Yodo river levee in 1995

Because of the occurrence of more than 3-m subsidence at the levee crest, it was found that the high tide near the river mouth is virtually a flooding that occurs twice a day. This is particularly important because the ground level behind the levee is lower than the sea level, being highly vulnerable to inundation in case of possible levee breaching. Thus, this is one of the examples of the compound effect of earthquake shaking and "flooding."

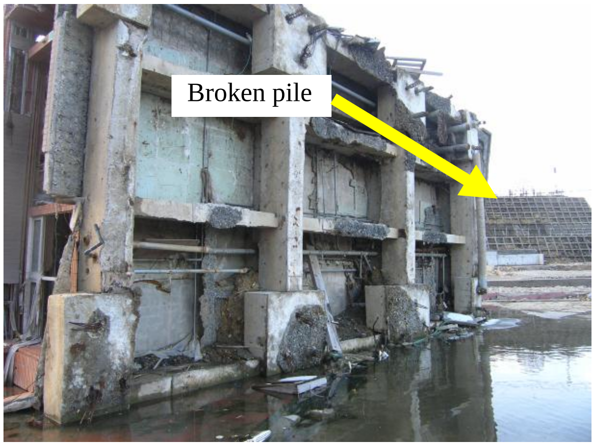


Fig. 2. Pile foundation of an overturned building in 2011 in Onagawa

It is imagined that liquefaction and tsunami action can exert a compound effect on building foundations. Fig. 2 illustrates the bottom of a building that was overturned by tsunami force. See its broken pile foundation. Apparently, the pull-out resistance of piles was not sufficient. The onset of subsoil liquefaction possibly reduced the pull-out resistance, although there is no evidence of liquefaction because everything was washed away by tsunami. Thus, the future design of tsunami-resistant building as a refugee place has to take into account the reduction of pull-out resistance (reduction of effective stress) caused by excess pore water pressure during shaking.

COMPOUND EFFECTS OF EARTHUQUAKE AND HEAVY RAINFALL IN SLOPE INSTABIILITY

One of the main themes of this paper is the slope instability during earthquakes. Traditionally both practical and research understood that seismic slope failures are triggered by the strong earthquake force (Fig. 3) and paid much attention to the factor of safety under dynamic load as well as quick rescue and restoration after a disaster. Recent experiences, however, exhibit different cases where earthquake-affected slopes fail sometime afterwards.

Figures 4 and 5 illustrate the consequence in Yinchanggou, Sichuan Province of China, where rainfall-induced debris flow started to attack this once-famous summer resort. This bad situation was caused by the seismically-destabilized slopes in the mountains behind this town (Fig. 6).

Fig.3. Earthquake-induced failure of mountain slope with Li Jia Village on (2008 Wenchuan earthquake in China)

Fig.4.Consequence of debris flow in Yinchanggou *in September, 2008, after the Wenchuan earthquake in May of the same year*

Fig.5. Yinchanggou *in October, 2012, after repeated debris flow during rainy seasons*

Fig.6. Unstable mountain slopes during rain behind Yin-changgou *(October, 2012)*

Fig. 7. Earthquake-induced crack in mountain slope (North Pakistan, October, 2005)

Fig. 8. Seismically affected slope behind Muzaffarabad of Pakistan

Fig. 9. Details of unstable slope behind Muzaffarabad(summer, 2008)

Fig. 10. Unstable debris deposits in valley bottom at Wenjiagou of Qingping of Sichuan Province)

A more detailed situation of a seismically-destabilized slope is illustrated in Fig. 7. After a gigantic earthquake in North Pakistan, 2005, a reconnaissance was made by the author. This figure indicates a big crack in a mountain slope after the earthquake and rain water can easily percolate into the slope through it, affecting the long-term slope stability.

Another mechanism of the compound effect is found in the continuous failure of mountain slopes behind Muzaffarabad, Pakistan after the 2005 earthquake. Although this slope was stable before the earthquake, debris flow started to occur frequently thereafter (Fig. 8). As shown in Fig. 9, there is no such a big crack in this figure as in Fig. 7 and it is supposed that the stronger shaking deteriorated the stone by developing many micro cracks and fissures.

A totally different mechanism of a long-term compound effect is shown in Fig. 10. The 2008 Wenchuan earthquake triggered many gigantic slope failures as stated above and this figure illustrates a typical situation in valleys afterwards. In August of 2010, heavy rainfall in this area caused a huge size of debris flow to start from this unstable deposit. Because a similar debris flow had caused a disastrous damage in Zhouqu County to the north one week prior (Ma, 2010), the local government issued wisely an evacuation order to people and successfully avoided a repetition of the tragedy. However, structures in a local town at the exit of this hazardous valley were destroyed. It should be stated, therefore, that local urban or regional planning must refrain from locating human settlements in disaster-prone sites.

In summary, there seems to be three kinds of long-term compound effects. They are caused by earthquake shaking first, and are followed by heavy rains. During rains, big cracks, minor fissures, or valley-bottom deposits aggravate the situation. Table1 summarizes them.

Table 1 Three kinds of earthquake-rainfall compound effects on long-term instability of slopes

Mechanisms	Effects on material properties?	Lasting time of instability
Crack opening and flow of surface water into soil	Generally no, but, if clay mineral absorbs water, swells, and deteriorates, yes.	Ending when slope with cracks falls down, but swelling effect may continue long.
Seismic disturbance and deterioration of material properties	Yes. Cementation and bonding are destroyed.	Quick recovery of deterioration is unlikely.
Washing out of debris deposits	No.	Ending upon washing out

DURATION OF COMPOUND LONG-TERM EFFECTS

It is important to have an idea how long the compound effects of earthquake and rain-fall lasts in reality. In some cases, vegetation recovers in a few years after a quake and no more debris is produced from the slope. In Taiwan, in contrast, the 1999 Chi-Chi earthquake continued its effects for a decade. Fig. 11 exhibits mountain slopes immediately after the earthquake. Surface materials were lost and the base materials are exposed to the environment. Because of the significant annual precipitation and active tectonic environment as well as the geologically young age of the island (of the order of 20 million years), the rock in the mountain slopes are soft, prone to weathering and fractured, making the long compound effect to be substantial. Consequently, as Fig. 12 shows, many debris flows started to occur during typhoons in the first ten years of the 21st Century (Lin et al., 2010, Yu et al., 2006). Furthermore, Fig. 13 shows the history of siltation (transportation of debris) in the reservoir of Tsengwen Dam. It is possible to suppose here that the rate of siltation increased after the Chi-Chi earthquake in Taiwan. Although the worst event in 2009 during the Typhoon Morakot was dominantly produced by the extreme amount of rain (Lee and Towhata, 2010), it is still possible that the previous earthquake affected the resistance of mountain slopes against rain and erosion. After the 1995 Kobe earthquake, similarly, the mountain slope behind the city became unstable (Okimura et al., 1999).

Fig. 11. Damaged mountain slope in Taiwan immediately after the 1999 Chi-Chi earthquake

Fig. 12. Debris flow in Taiwan in 2008.

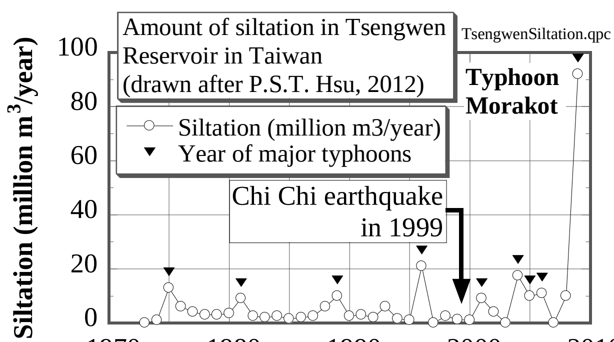


Fig. 13. Records of siltation in Tsengwen Dam reservoir in South Taiwan (data supplied by Hsu (2012))

Fig. 14. Continued instability of Ohya landslide site

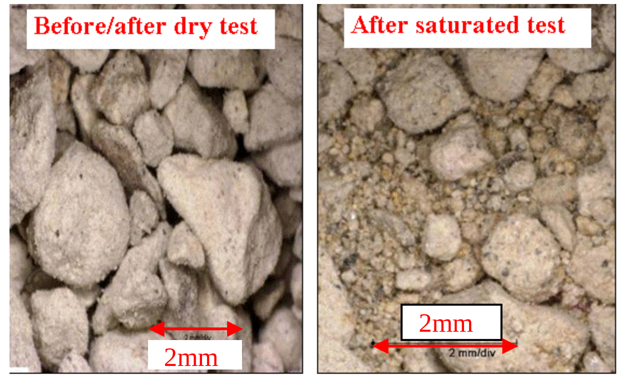


Fig. 15. Deterioration of crushed sandy mudstone upon water submergence

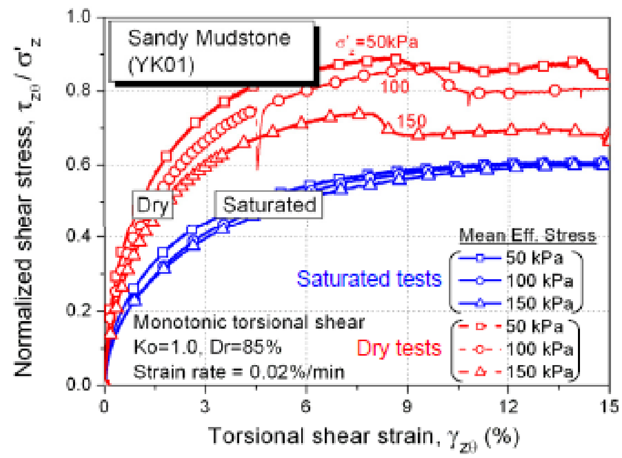


Fig. 16. Deterioration of crushed sandy mudstone upon water submergence

A more evident and profound effect of precedent earthquake can be found at the site of Ohya landslide, which is located at about 100 km to the west of Tokyo; see Fig. 14. It is said that this landslide originates from a big failure induced by a gigantic earthquake of Mw = 8.7 in 1707 or even an earlier one (Takeuchi and Tsutsumi, 1985) that occurred in the subduction zone in the Pacific Ocean. Since then, for hundreds of years, this site has been producing debris flows during heavy rains. Thus, it is possible that the compound effect lasts for a long time if the environmental and geological situations are adverse.

ROCKS VULNERABLE TO THE COMPUND EFFECTS

When the author visited the Ohya site, it was found that the mountain slope was covered by pieces of stone that were flat in shape and 20-30cm in size. It was felt therefore that the mother rock had been fractured into such pieces by some mechanism. Although there is no evidence, it seems that the temperature change and in particular the expansion of formed ice in fractures during the cold winter are possible mechanisms of breakage. Another possible mechanism is the effects of water, which is called hydration herein, on rocks. Whether temperature or water, their influence becomes significant once the surface rock/stone coverage is lost during the earthquake-induced slope failure and the underlying material becomes exposed to the harsh environment.

Aziz et al. (2011) carried out hydration tests on different rock specimens. Fig. 15 illustrates grain particles before and after water submergence. Being similar to slaking tests, the water submergence without dynamic effects deteriorated grains of crushed the mudstone. As a consequence, the mechanical strength of crushed mudstone is reduced. In the test of Fig. 16, a dry specimen of crushed mudstone was submerged in water under confining pressure of 50-150 kPa in a triaxial specimen. By comparing the test result of drained triaxial compression test of this specimen with that of a dry specimen, the reduction of strength is observed. The extent of reduction is demonstrated in Fig. 16 in which the specimens are similarly deteriorated under different pressures.

SEARCHING FOR PEOPLE'S KNOWLEGE FOR DISASTER MITIGATION

The long-term effect is mostly a problem in mountainous regions where construction of costly retaining walls, rock anchorage and other stabilization measures are impractical. Hence, other feasible measures have to be sought for. Certainly, hazard mapping is a useful tool. However, the evaluation of the extent of instability in practice does not have a sufficient financial support and execution of in-situ tests or collection of samples for mechanical test is not easy. Accordingly, the practice resorts to interpretation of topographic and geological data without much information on mechanical properties. Therefore, the hazard assessment often becomes conservative.

This situation implies a limitation of the geotechnical engineering approach so far achieved. In this approach, the behavior of the target material, which is the deteriorated rock underlying a slope in this paper, is investigated and modeled, and then the effects of the external actions such as the earthquake loading and rain falls are evaluated. Then a judgment is made whether or not the studied slope is stable. Although this approach is rational or scientific, its shortcoming is that many kinds of precise data are required for successful assessment. Because the reality does not necessarily allow expensive site investigation for data, a different methodology has to be pursued.

This chapter briefly addresses two findings of possible wisdom of people. Fig. 17 was taken in Yamakoshi Village where the 2004 Niigata-Chuetsu earthquake caused many slope failures. It is interesting that people's houses in this photograph are situated on stable parts of slopes while surrounding slopes deformed or failed. This situation was in good contrast with damage of livestock houses and public buildings in the same village that were located on unstable slopes. It was impressed during this field study that the village history of 1000 years gave people non-engineering knowledge where to live. Possibly, modern geotechnical engineering is not fully developed to know everything.

Fig. 17. Safe location of residences in earthquake-affected Yamakoshi Village of Niigata-Chuetsu in 2004

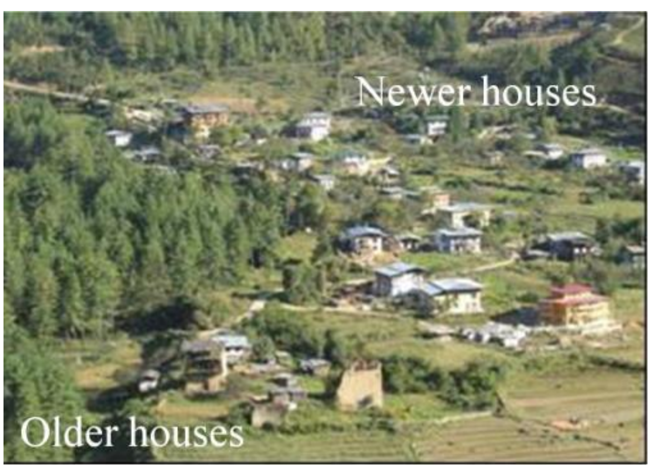


Fig. 18. Safe location of residences in fluvial fun where flooding and debris flow are possible to occur (Thimphu, Bhutan)

Another wisdom was found upon a fluvial fun near Thimphu, the capital of Bhutan. Fig. 18 shows that older houses are located behind a forest probably for protection from flooding and debris flow, whereas newer houses are located near the center of the fun which is more vulnerable to natural disasters. It is possible that the modern people are missing the traditional wisdom because of the reducing encountering with natural disasters. Because the number of evidences is not yet sufficient, it is desired to conduct more studies on traditional non-engineering wisdom in mountainous regions where people have been living for centuries.

STRATEGY TO COPE WITH UNSTABLE MOUNTAIN SLOPES

The ongoing study by the author's group puts emphasis on practical screening of potentially unstable slopes (Qureshi et al., 2009) and, if necessary, development of early-warning technology for successful evacuation (Uchimura et al., 2009 and 2011). Although still under development, the general story of this technology may be summarized as what follows;

1) primary screening on the basis of topography, history of past disasters, and vulnerable community,
2) secondary screening by means of simple field investigation such as geophysical methods,
3) installation of monitoring instruments in the slope for early warning and their connection to an internet system, and
4) although costly, construction of retaining walls or other stabilizing measures if financially feasible.

Among these four stages, 1) and 4) have been conducted in many places. Therefore, this chapter describes 2) and 3).

SCREENING BY GEOPHYSICAL MEHOD

Shear strength of geomaterials that compose a slope is a key mechanical property that governs the instability of a slope during heavy rainfall. The preceding earthquakes together with continuing process of weathering / deterioration reduce the factor of safety with time. Therefore, any field investigation on potentially vulnerable slopes has to be conducted repeatedly so that the change of the situation may be monitored.

Collection of undisturbed samples (coring) of rock is not an easy task in mountain slopes, although the target of slope instability study is not a hard rock but softer and deteriorated materials. On the other hand, the second screening has to investigate local condition more elaborately than simply relying on empiricism as the first screening does. In this regard, the present study attempts to use a geophysical method that does not require drilling holes in a mountain slope (Qureshi et al., 2012).

Figure 19 illustrates an ongoing S-wave velocity (Vs) measurement (seismic refraction survey) for which geo-phones are deployed along the ground surface and shaking is produced by vertical impact of a hammer on the slope surface. Whether the involved ground motion is that of S wave or Rayleigh wave, their propagation velocities are of minor difference (less than 10% or possibly 5%), which is geotechnically negligible. By using the traditional method of data interpretation, Vs and the thickness of the surface weak layer are determined. The aim of the Vs survey is a development of relationship between Vs, which is easily measured in the field, and shear strength parameter of the slope, which is essential in a slope instability judgment. To obtain the strength for this research, portable cone penetration tests were run as well. For this test, a hammer of 5 kg mass falls 50 cm and the number of blows (N_d) for 10 cm penetration of the cone tip (60 degrees and 2.5 cm in diameter) is counted (Fig. 20).

Figure 21 illustrates an example of this type of study and compares the thickness of the surface layer with what was obtained from portable dynamic cone penetration tests. The extent of agreement between two independent field investigations is reasonable for this type of studies. The number of blows was converted to shear strength by

$$SPT-N=(1-3)N_d$$
$$\phi=31.2\sqrt{\frac{N}{\sigma_v'\ (kPa)+68.65}}.+25 \qquad (1)$$

Fig. 19. Seismic refraction survey upon weathered mountain slope (near Ikezawa Pass, Nagano)

Fig. 20. Portable dynamic cone penetration test (near Ikezawa Pass, Nagano)

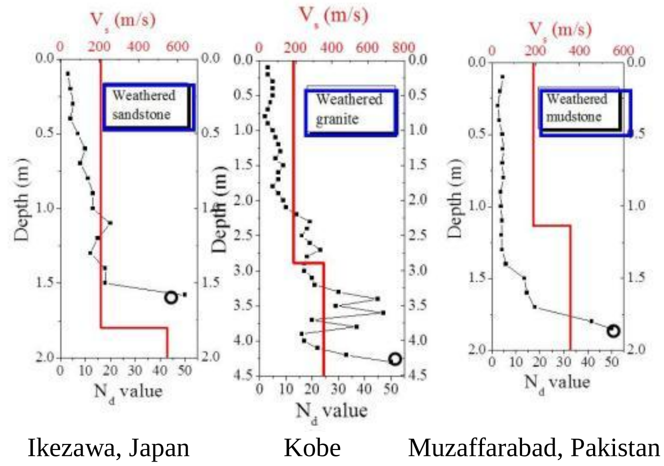


Fig. 21. Thickness of surface weak layer in a mountain slope studied by geophysical method and dynamic cone penetration

(1)

In addition to the field investigations, unconfined compression tests were run on rock specimens that were deteriorated by repeated freezing and thawing accompanied by water submergence. This series of tests are considered to be a laboratory reproduction of mechanical weathering (development of fissures and joints) caused by volume expansion of freezing water (ice formation); refer to Qureshi (2012). Modulus of specimens at very small strain (less than 10^{-3}%) was measured and converted to an equivalent S-wave velocity by

$$V_s=\sqrt{G_{\max}/\rho} \qquad (2)$$

where $G_{\max}$ and ρ stand for the shear modulus at small strain and mass density, respectively.

Figure 22 plots V_s against the shear strength from both laboratory and field studies. Among two groups of data, those from laboratory unconfined compression tests represent the nature of relatively intact and stable rock slopes. This interpretation is reasonable because the tested specimens maintained their cylindrical shape during unconfined compression. In contrast, the data from the field was obtained from deteriorated slopes (Eq. 1) where the original rock had been broken into fractures. Hence, this group of data should be employed for the screening of the slope.

In practice, Vs measurement is repeated at a reasonable time interval so that the decay of materials with years may be traced. From the measured Vs, the data in Fig. 20 gives an approximate value of shear strength. Because the surface of slopes is dry when the measurements are taken, avoiding rainy days, this strength should be converted to the strength when submerged in ground water during heavy rains. By assuming frictional behavior of fractured rocks and the elevation of the ground water at the surface as an extreme rain condition, the shear strength after full submergence is determined and compared with the working shear stress during rain. In this manner, the factor of safety during heavy rain is assessed. If the safety factor comes close to unity, the early warning equipments should be installed.

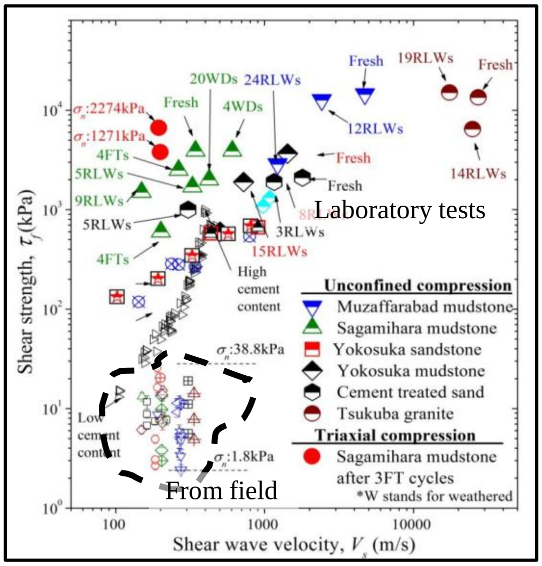


Fig. 22. Experimental relationship between shear wave velocity and shear strength of weathered rocks and slopes (Nong et al., 2012)

SLOPE MONITORING AND EARLY WARNING

As stated elsewhere (Uchimura, 2009), the developed device is essentially a tiltometer. This device is placed at the top of a vertical rod that is pushed through the surface unstable layer downward until it encounters the base stable layer (Fig. 23). When the surface layer becomes unstable and starts minor movement during heavy rain, the vertical rod is pushed in the down-slope direction, while its bottom is somehow fixed in the stable base. Consequently, the rod rotates and the tilting angle is monitored by the sensor. Note that a larger deep-seated slope failure is out of scope without significant problems. This is because the majority of damaging slope failures is of minor scale, occurring within the surface weathered part, and even larger ones may be accompanied by rotational movement as implied by the theory of a circular slip surface.

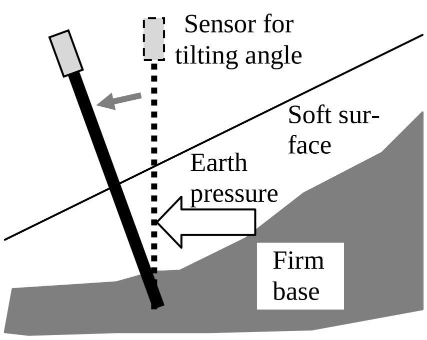
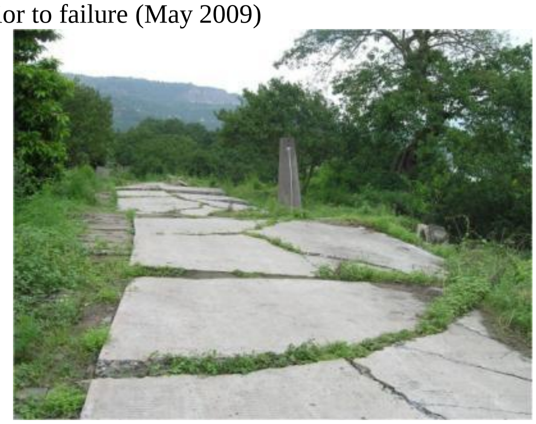


Fig. 23. Working principle of tiltometer for early warning

The authors' study on early warning technology has specific features as followings:

1) Sensors should be deployed at as many locations as possible on the concerned slope because it is difficult to know in advance which part of the slope would fail in reality.
2) Hence, an individual sensor should be inexpensive in order to keep the whole installation cost within a reasonable extent.
3) The use of a solar battery was avoided for cost reduction; as an alternative, for ordinary batteries are employed with special algorithm of monitoring to make the battery life longer than one year.
4) Good human relationship with local authorities and people is very important for good maintenance of the device. It should be further stressed that early warning helps them from the disaster of slope failure.
5) The monitored data is sent through INTERNET to an expert in order to interpret it and issue, if necessary, an emergency caution and warning.

(a) Prior to failure (May 2009)



(b) After failure on 7th of June, 2009

Fig. 24. Monitored slope along the Three Gorge Dam Reservoir, China

Figure 24 illustrates one of the monitored unstable slopes along the Three Gorge Reservoir of China. The filling of the reservoir after completion of the dam induced loss of effective stress in the lower part of slopes and, consequently, many slope failures occurred. At this particular site, a failure occurred on June 7th, 2009.

The data of the tilting angle is illustrated in Fig. 25. Prior to the final failure on June 7th to 8th, the tilting angle had been increasing gradually at the rate of more or less 0.0008 deg/hour. In the final stage, the rate of the tilting angle increased to 0.13 deg/hour. Because this final stage lasted for a few days, it is possible to issue an evacuation order well in advance if a reasonable threshold criterion is established in the rate of tilting angle. In the current stage, the author is proposing two criteria:

- Caution if > 0.005degree / hour, and
- Alert or evacuation if > 0.1 deg/hour.

which are consistent with the observations in Fig. 25 and those at other sites.

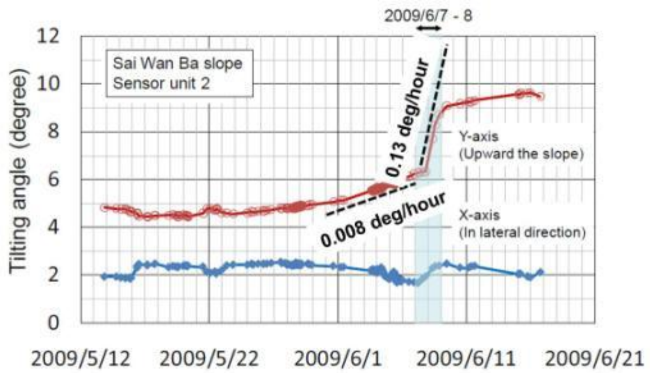


Fig. 25. Time history of data of tiltometer at the Three Gorge Dam site (Uchimura et al., 2011)

SUMMARY AND CONCLUSION

The present paper addresses the problem of slope instability induced by earthquakes. While many studies have concerned with the slope failures that were directly caused by the earthquake ground motion, the present paper is interested in the long-term problems that are caused by the compound effects of the earthquake motion followed by rain falls. After introducing several examples of the compound effects, the following conclusions were drawn.

1) The mechanisms of the compound effects were classified into three types that are namely cracks, minor deteriorations, and valley bottom deposits.
2) Because the first two of the above three are related with the effects of water, test results were introduced on the water-induced deterioration of soft rocks.
3) For mitigation of the long-term slope instability, monitoring and early warning are important.
4) For screening the particularly unstable slopes in which deterioration proceeds with time, the measurement of shear wave velocity is proposed; the measured wave velocity is related with the shear strength of slope materials.
5) If the measured wave velocity suggests incipient slope failure during heavy rainfall, monitoring equipments should be installed. Threshold values of monitored data are proposed for the first caution and the final alert for evacuation.
6)

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